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Wideband Full-Corporate-Feed Waveguide Continuous Transverse Stub Antenna Array

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ABSTRACT A Ka-band waveguide continuous transverse stub antenna array with full-corporate-feed network is presented in this paper. Multiple-section stepped-impedance transformers are used for wideband impedance matching of the radiation slots. The required high-quality quasi-TEM wave excitation is generated by a wideband plane-wave generator (WPWG). Compared with the conventional pillbox structure, the WPWG produces a quasi-TEM wave with more uniform amplitude distribution. By using the combination of these design features, significant increases both in bandwidth and antenna aperture efficiency are achieved. For demonstration, a prototype is designed, fabricated, and measured. Excellent agreement is achieved between simulations and measurements. The antenna is matched over the entire Ka-band of 26–40 GHz. A high antenna aperture efficiency of over 75% and a low cross-polarization of less than –46 dB are achieved over the entire bandwidth. The demonstrated features of wideband, high aperture efficiency, and low cross-polarization have great potentials for millimeter-wave applications.

INDEX TERMS Wideband antenna array, continuous transverse stub antenna, aperture efficiency, wideband plane wave generator, full-corporate-feed network.

I. INTRODUCTION

The millimeter-wave (MMW) frequencies of 26.5–29.5 GHz and 37–40 GHz, contained in Ka-band, have been allocated to new 5G radio access [1]. The Ka-band itself has already been widely used in satellite communications. Wideband high gain antennas with low cross-polarization and high aperture efficiency are highly desired for such applications [2], [3]. Microstrip, substrate-integrated waveguide (SIW) and hollow waveguide antennas are the common technologies. At these high frequencies, the microstrip lines and SIW waveguides experience high dielectric losses in the feeding network. The losses become critically significant when designing large feeding networks for high-gain antenna arrays [4]–[7]. Hollow waveguide has much lower losses in general and slotted waveguide (SW) array has been a good choice for high performance MMW antennas. But SW arrays commonly suffer from a narrow bandwidth [8]–[12]. Recently, a diffusion

bonding based fabrication technology has been applied to SW arrays, and the achieved bandwidth varied between 10% and 19% [13]–[15]. Ridge gap waveguide technology has also been used in wideband MMW antenna array design [16]. A gain of over 27.5 dBi was achieved over a 30% impedance bandwidth (50–67.8 GHz).

Continuous transverse stub (CTS) antenna arrays have long been considered a competitive hollow-waveguide technology for high gain and high efficiency antennas at MMW frequencies [17], [18]. Some work has been done in the past few years. A 32-slot CTS antenna array with 19% impedance bandwidth from 71–86 GHz was shown in [19]. In [20], a CTS antenna array based on low temperature co-fired ceramic (LTCC) technology was reported. The antenna realized over 25% fractional bandwidth from 51.2–66 GHz. Most of these CTS antennas adopted a pillbox coupler configuration as the TE₁₀ to quasi-TEM wave converter. Due to the relatively

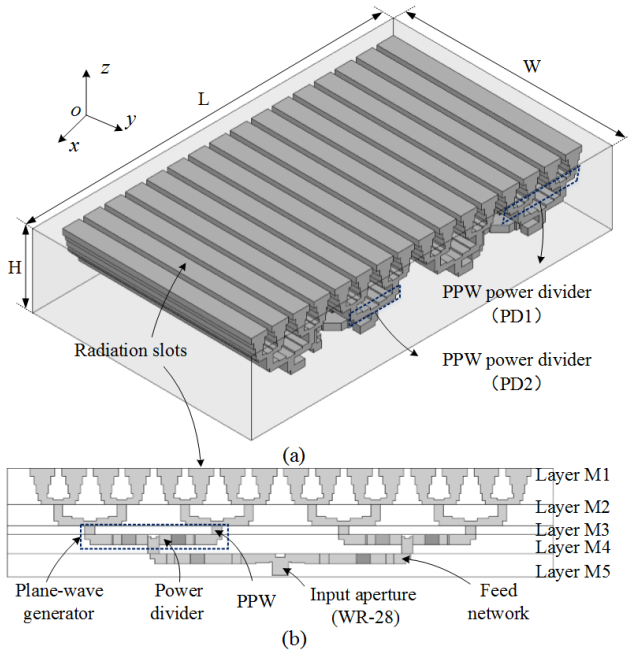


FIGURE 1. Configuration of the proposed CTS array. (a) 3-D overview; (b) Cross-sectional view. It should be noted that the grey areas are the ‘air cavities’.

narrow band characteristic of such a converter, the reported bandwidth of CTS and SW antennas so far was limited to 30 %. In addition, the amplitude distribution of the pillbox coupler normally exhibits a fall-off at the aperture edges, which causes significant reduction in the antenna aperture efficiency.

In this paper, a CTS antenna array with over 42% fractional bandwidth from 26-40 GHz covering the whole Ka-band is presented. Unlike the conventional pillbox coupler, a multiple-port excited wideband plane-wave generator (WPWG) is proposed to boost the conversion bandwidth from TE_{10} to high quality quasi-TEM wave. The amplitude distribution of the WPWG is examined in detail. By combining the wideband radiation structures with a full-corporate-feed networks, the bandwidth of the whole CTS antenna array has been significantly enhanced. In addition, with a more uniform amplitude distribution of the WPWG, the antenna aperture efficiency has been shown to improve effectively. To validate the design, a prototype array operating at Ka-band is fabricated and measured.

II. ANTENNA DESIGN AND ANALYSIS

The configuration of the proposed wideband CTS antenna array is shown in Fig. 1. It contains sixteen radiation slots and a full-corporate-feed network. The signal flow in the antennas is as follows:

- 1) The signal coming from the standard WR28 input waveguide port is divided into multiple paths by a 1-to-8 feed network in M5. A good impedance

matching is required between the input hollow-waveguide and single-ridge waveguide.

- 2) The feed network is followed by two wideband plane-wave generators (WPWGs) in M3 and M4. The WPWG converts the TE_{10} mode in the single-ridge waveguide into a quasi-TEM wave in PPW with a wide operating band and uniform amplitude distribution. It is noted that the width of the CTS array is determined by the total width of the PPW in the WPWG, and it can be extended by adding the number of the excitation ports.
- 3) The four quasi-TEM wave outputs from M3 enter into four PPW power dividers in M2. Each of the divider outputs feeds into two radiation slots. The number of PPW power dividers is determined by the number of radiation slots.
- 4) Finally, the electromagnetic wave radiates from the sixteen CTS slots in M1. A multiple-section stepped impedance transformer (MSSIT) is loaded at each radiation slot to increase the operating bandwidth. The length of the radiation slots determines the number of the divisions in the feeding network. 8 divisions are needed in M5 in this design.

Next the radiation slot, PPW power divider, WPWG and feed network will be discussed in more details.

A. RADIATION SLOTS AND PPW POWER DIVIDERS

The radiation performance of the array is mainly determined by the radiation slot width a and period d_x shown in Fig. 2. According the analysis in [21], for broadband operation, the value of d_x/a should be close to 1. This means that the metal wall between the adjacent radiation slots should be as thin as possible. In consideration of the manufacturability, the value of d_x/a is set to be 1.4 in this design. To avoid grating lobes over the whole operating band, the period d_x should be less than the free-space wavelength of the highest operating frequency. In this work, the array is designed to operate over the entire Ka-band (26 to 40 GHz). With the free-space wavelength of 7.5 mm at 40 GHz, we choose $d_x = 7$ mm and $a = 5.5$ mm.

Fig. 2(a) shows the radiation unit, consisting of two radiation slots, two multiple-section stepped impedance transformer (MSSITs) and a PPW power divider in layer M1. The MSSIT is used to realize a wideband impedance matching between the radiation slot and output of the PPW power divider (named PD1). Fig. 3 shows the equivalent circuit of the MSSIT. The reflection coefficient from the input of the MSSIT can be calculated as [22]:

$$|\Gamma(\theta)| = \begin{cases} |\Gamma_0 \cos N\theta + \dots + \Gamma_n \cos(N-2n)\theta + \dots + \frac{1}{2}\Gamma_{N/2}|, & N \in \text{even} \\ |\Gamma_0 \cos N\theta + \dots + \Gamma_n \cos(N-2n)\theta + \dots + \Gamma_{(N-1)/2} \cos \theta|, & N \in \text{odd} \end{cases} \quad (1)$$

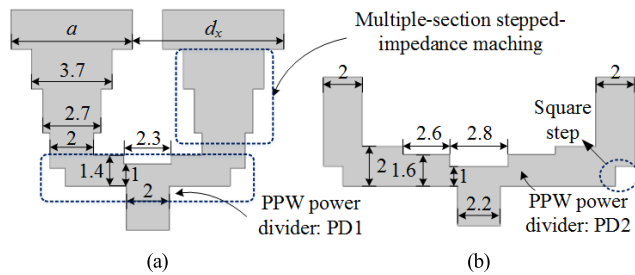


FIGURE 2. (a) Radiation unit; (b) PPW power divider in M2. All dimensions are given in millimeters.

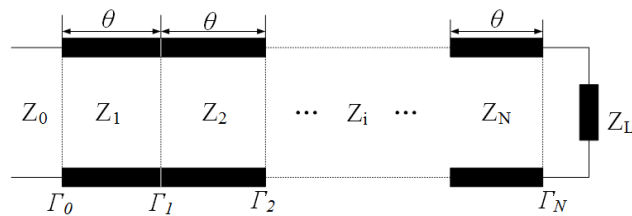


FIGURE 3. Equivalent circuit of the MSSIT.

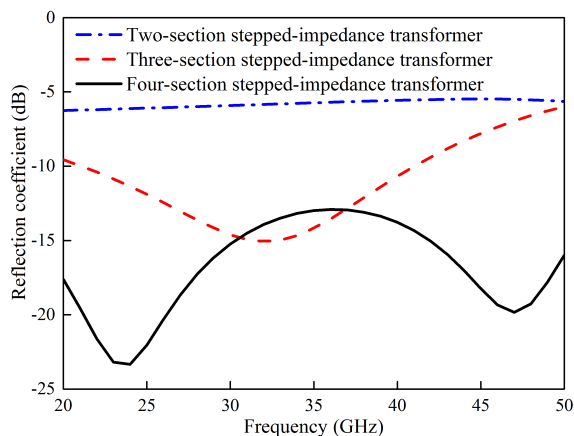


FIGURE 4. Impedance matching under different number of MSSIT.

where $\Gamma_i = (Z_{i+1} - Z_i)/(Z_{i+1} + Z_i)$, $i = 0, 1, 2, \dots, N$ is the total section number. Z_i is the characteristic impedance of the i -th line section, and Z_L ($120\pi\Omega$ in free-space) is the load.

Fig. 4 shows the simulated reflection coefficient of the MSSIT with different numbers of sections. It can be seen that the bandwidth increases with the number of sections. When this number is more than 3, the impedance bandwidth ($|S_{11}| < -10$ dB) can cover the whole Ka-band.

There are two types of PPW power dividers, namely PD1 and PD2, in layer M1 and M2, as shown in Fig. 2 (a) and (b) respectively. PD1 and PD2 form a four-way divider and feed the MSSITs to excite the radiation slots. It is noted that the width of the input port of PD2 is the same as the height of the PPW in the WPWG (shown in Fig. 9), which is also equal to the height of the single-ridge waveguide. In this way, no extra transition structure is needed between

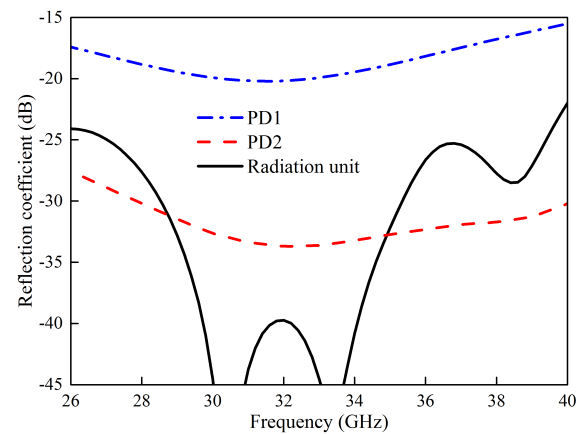


FIGURE 5. Simulated reflection coefficients of the radiation unit and the PPW power divider in M1, M2.

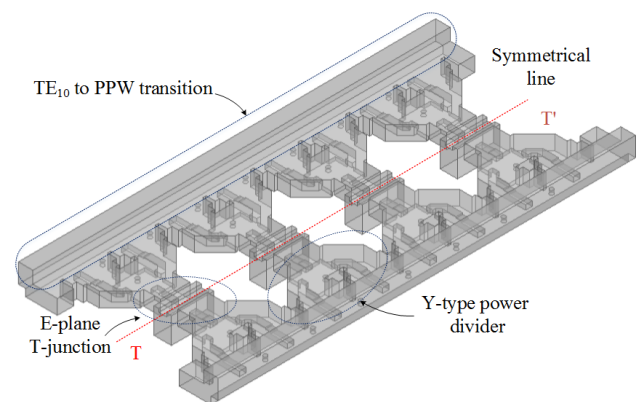


FIGURE 6. Structure of the wideband plane wave generator (WPWG).

the input of PD2 and the output of WPWG (shown in Fig. 1). As the operating band of the single-ridge waveguide covers the Ka-band, its cutoff frequency is lower than 26 GHz. Thus, the height of the single-ridge waveguide is chosen to be 2.2 mm. Besides, a square step (shown in Fig. 2) is added at the bend of the output PPW to improve the impedance matching [23]. The optimized dimensions of the radiation units and PD2 are given in Fig. 2. The simulated reflection coefficients of PD1, PD2 and the radiation unit are shown in Fig. 5. The reflection coefficient of the radiation unit is lower than -22 dB.

B. WIDEBAND PLANE WAVE GENERATOR

The WPWG is employed to generate quasi-TEM wave as required to excite the radiation slots. Fig. 6 is the 3D-view of the proposed structure. It consists of four 1-to-4 single-ridge waveguide power dividers and two PPWs excited by 8 ports. It is worth mentioning that one WPWG generates two ways of quasi-TEM wave, because the symmetrical distribution of output ports in the 1-to-4 power dividers. The bandwidth of the WPWG should cover 26-40 GHz. Next, we will discuss

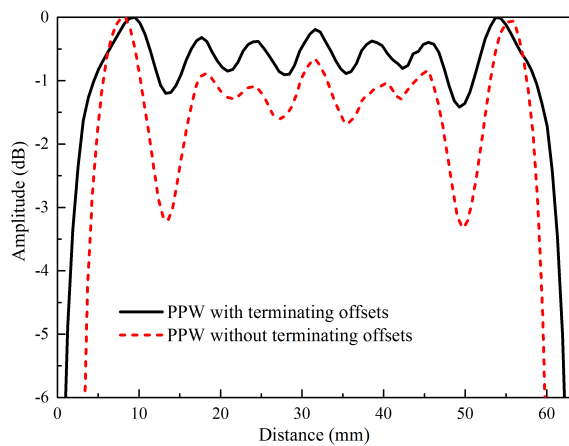


FIGURE 10. E-field amplitude fluctuation with and without the $\lambda_0/4$ terminating offsets at 33 GHz.

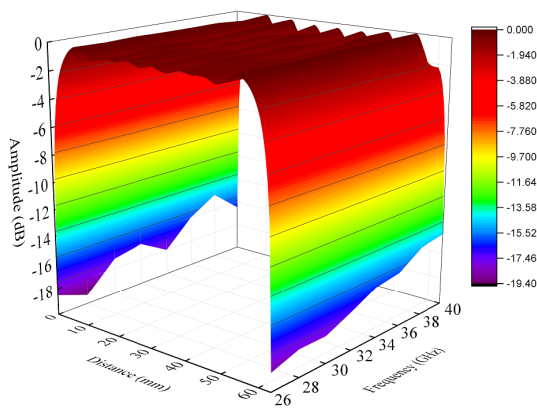


FIGURE 11. E-field variation of the quasi-TEM wave in the PPW over the frequency band of 26-40 GHz.

opposite. But with the symmetrical distribution of the eight output ports, the phase differences between the ports 2, 3, 4, 5 and ports 6, 7, 8, 9 are reversed to be in-phase. The E- and H-plane T-junctions, as well as the transition structure are also shown separately in Fig. 12. To maintain wideband impedance matching, a capacitive board, marked out in Fig. 12(c), is embedded in each of the H-plane T-junction and two three-section impedance transformers are used [24], [25].

In order to realize wideband transition between the single-ridge waveguide and the hollow waveguide, a stepped ridge and hollow waveguide are involved. A square step is again loaded to the bend for matching [23]. The matching is mainly controlled by the heights of the stepped ridge and hollow waveguide: C_h and R_h , as shown in Fig. 13. The parameters study of this transition structure can be found in Fig. 13. When $C_h = 1.16$ mm and $R_h = 0.8$ mm, a reflection coefficient lower than -24 dB can be achieved over the bandwidth of 26 - 40 GHz.

The simulated amplitude responses of the 1-to-8 power divider are given in Fig. 14. The reflection coefficient is lower than -16 dB and all the transmission coefficients are

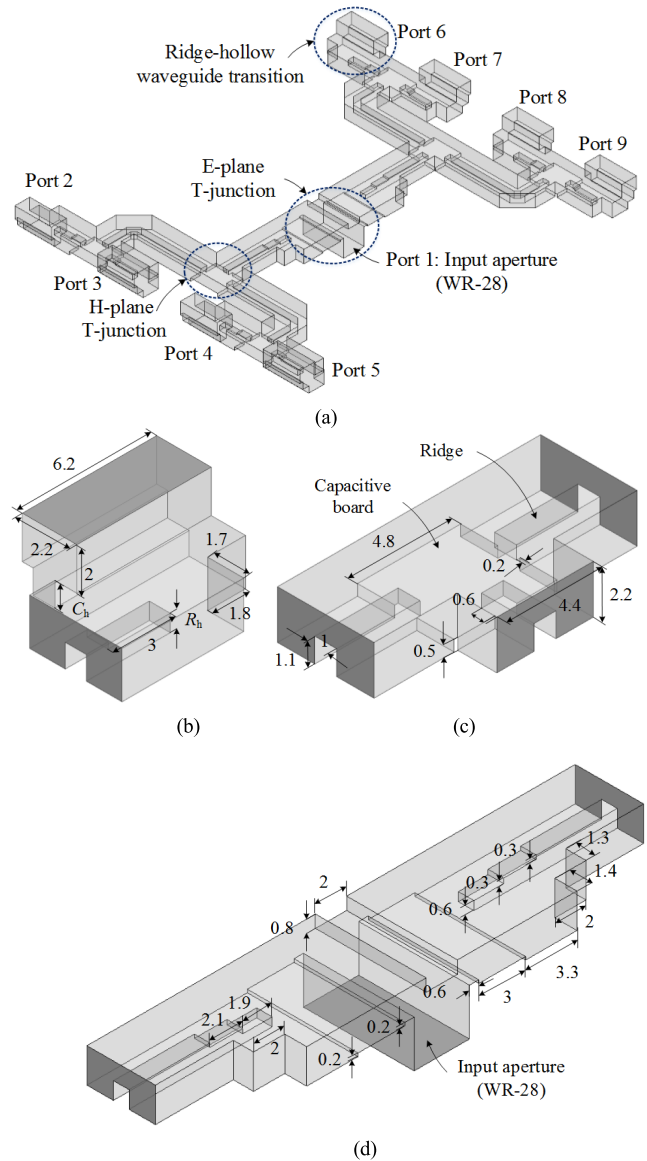


FIGURE 12. (a) 1-to-8 feed network; (b) Transition of single-ridge waveguide to hollow waveguide; (c) H-plane T-junction; (d) E-plane T-junction. All dimensions are given in millimeters.

within -9 ± 0.05 dB, exhibiting a good matching and output amplitude balance over the bandwidth of 26 to 40 GHz.

III. MEASUREMENTS AND DISCUSSION

The CTS antenna has been prototyped using aluminum blocks. To simplify the assembly, the layers M1 and M2 are merged to one block. A set of tightening screws are placed around the antenna to suppress wave leakage. The photographs of layers M1-M5 and the assembled CTS antenna array are given in Fig. 15. The overall sizes of the fabricated CTS antenna array are $126.5 \text{ mm} \times 79 \text{ mm} \times 30 \text{ mm}$ ($L \times W \times H$, shown in Fig. 1(a)). All the simulations are carried out with Ansoft HFSS. The radiation performances are measured using a small near-field vertical planar scanner system from NSI-MI Technologies.

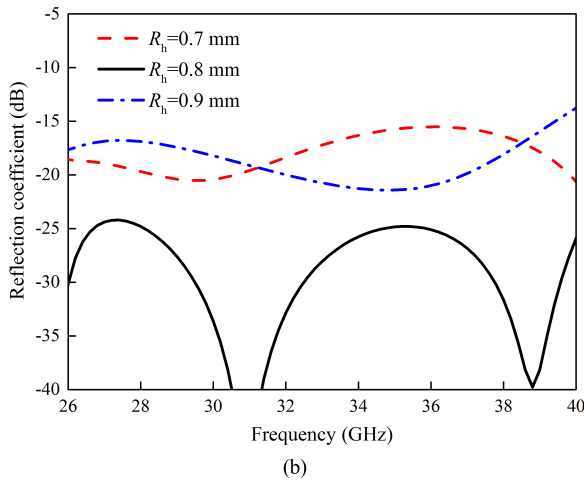
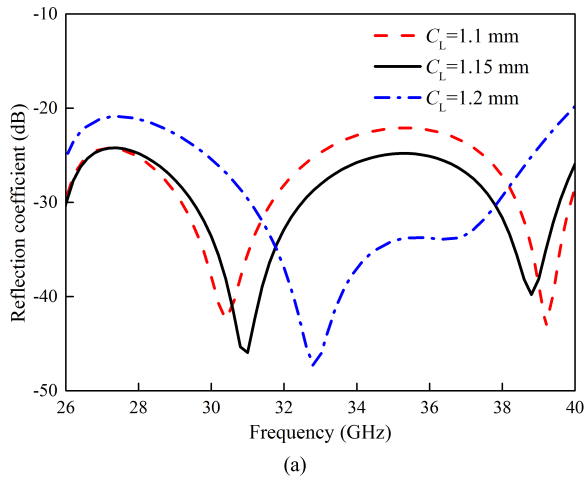


FIGURE 13. Impedance matching analysis of the transition structure in Fig. 12 (b): (a) different values of C_h , (b) different values of R_h .

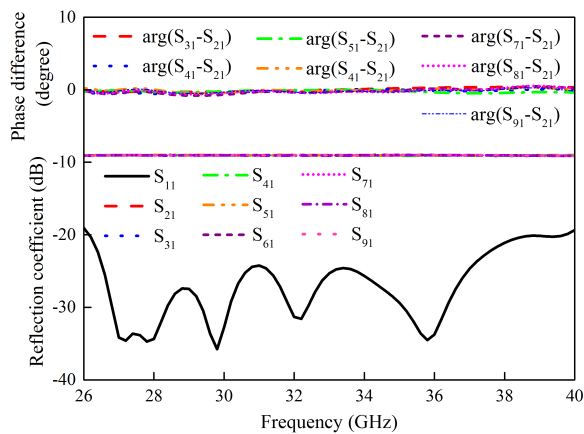


FIGURE 14. Simulated results of the feed network: amplitude and phase responses. The port numbers are shown in Fig. 12.

A. REFLECTION COEFFICIENT

The reflection coefficients are measured using Agilent E8361C network analyzer and shown in Fig. 16. They are in

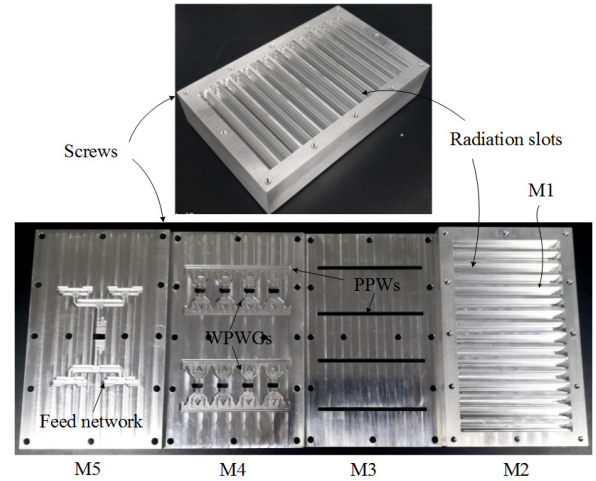


FIGURE 15. Photographs of the fabricated CTS antenna array.

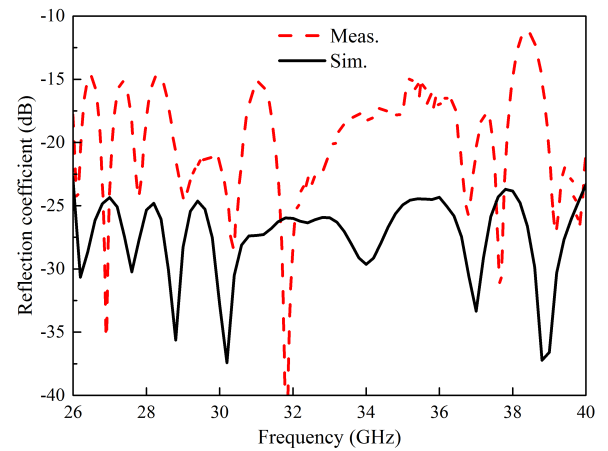


FIGURE 16. Simulated and measured reflection coefficients of the CTS antenna.

reasonably good agreement with simulations. The difference is mainly attributed to the assembly errors and fabrication tolerances. A matching ($|S_{11}| < -10$ dB) bandwidth of 42.4 % is achieved over 26 - 40 GHz.

B. RADIATION PATTERNS

Fig. 17 shows the simulated and measured normalized radiation patterns in the E- and H-planes at different frequencies. The measured results are very consistent with the simulations. The beam-widths at the E- and H-planes are determined by the number of radiations slots and the width of WPWG, respectively. The maximum 3-dB beam-widths are 5.2° and 10.4° at E- and H-planes over the whole band. The sidelobe levels (SLLs) at the E- and H-plane radiation patterns are around -13.3 dB and -12.1 dB. This is consistent with the sidelobes characteristics of an array with a uniform amplitude excitation. The measured cross-polarization levels are also plotted in Fig. 17. It shows a low cross-polarizations of better than -46 dB for both the E- and H-planes.

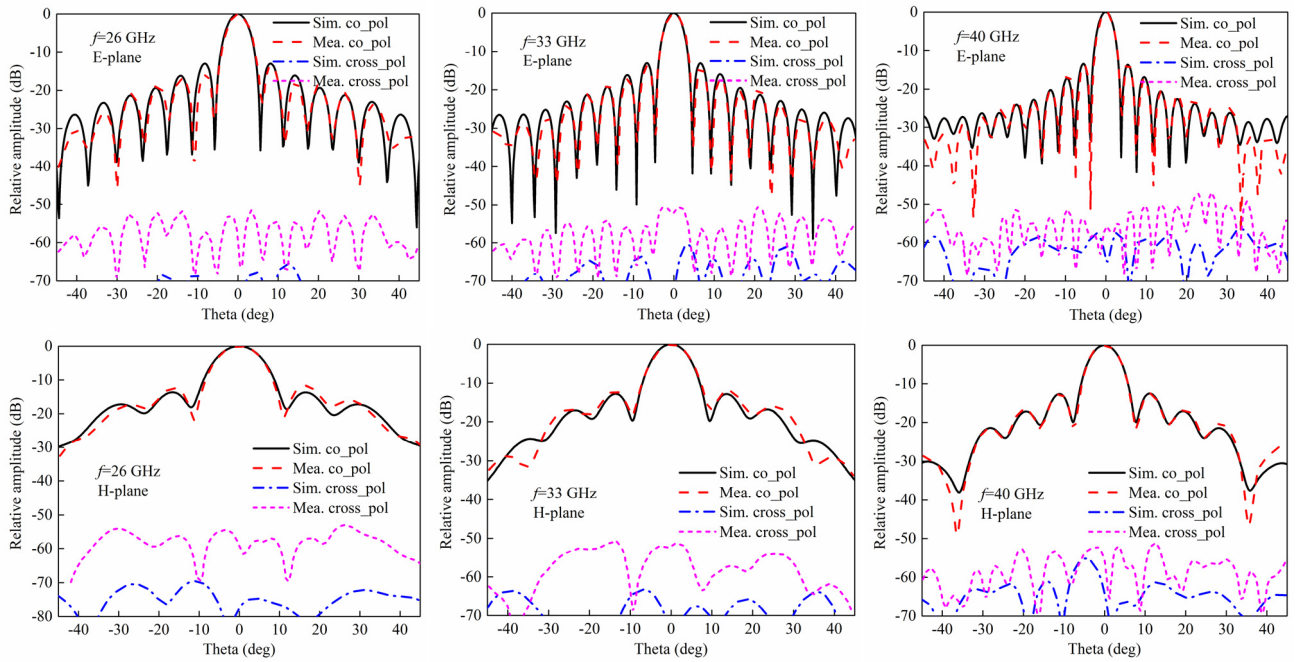


FIGURE 17. Simulated and measured radiation patterns: (a) 26 GHz; (b) 33 GHz; (c) 40 GHz.

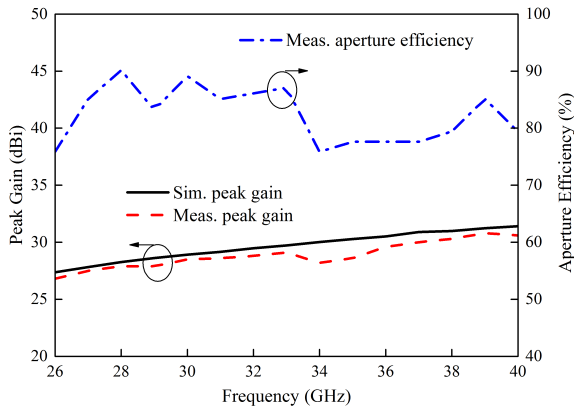


FIGURE 18. Simulated and measured peak gain and aperture efficiency.

C. PEAK GAIN AND APERTURE EFFICIENCY

The measured peak gain and antenna aperture efficiency as a function of the frequency are plotted in Fig. 18. At the center frequency of 33 GHz, a peak gain of 29.1 dBi and an aperture efficiency of 87.1% are recorded. With the help of the wideband WPWG, a high aperture efficiency of more than 75% is achieved over 26 - 40 GHz. The measured peak gain is slightly lower than the simulated. The small difference may be attributed to the assembly error and the fabrication tolerance.

D. COMPARISONS

Table I compares the performance of this design with several other published wideband waveguide arrays. Among

TABLE 1. Comparison of Waveguide Antenna Arrays.

Ref.	Type	Slots No.	BW (%)	Gain (dBi)	Eff. (%)	Size (λ_0^3)*
[15]	SW	16×16	20.4	>31.4	>70	15.7×15.7×0.8
[16]	SW	8×8	30	>25	>80	8.8×8.8×2.4
[19]	CTS	32	19	>30.8	>48	43.2×25.1×8.8
[20]	CTS (LTCC)	4	25.2	>11	>44	6.5×3.4×0.9
This work	CTS	16	42.4	>26.8	>75	12.3×6.7×2.8

* λ_0 is the free space wavelength at the center operating frequency.

them, [15] and [16] are based on SW, others are based on CTS. This work exhibits the largest fractional bandwidth, which is over 42%. Compared with the CTS antenna array in the previous work, the aperture efficiency of this work is improved significantly, due to the high quality quasi-TEM wave generated by the WPWG.

IV. CONCLUSION

In this paper, a wideband 16-slot CTS antenna array for Ka-band applications is demonstrated. A WPWG constructed of single-ridge power dividers and PPW is introduced to generate quasi-TEM wave. Compared with the conventional mode converter of pillbox, the proposed WPWG supports a wider operating band and produces quasi-TEM wave with uniform amplitude distribution. To enhance the operating band of the radiation slot, a MSSIT is employed and bandwidth characteristic is examined. For demonstration purpose, an experimental prototype with the operating band was designed

and implemented. Experimental results show that the proposed CTS antenna array has an impedance bandwidth of over 42% and aperture efficiency of more than 75% over the whole Ka band. Compared with the previous works, the proposed design shows a wider impedance bandwidth and higher aperture efficiency. It has demonstrated attractive features and potentials for millimeter-wave applications, such as 5G, wideband satellite communication, etc.

REFERENCES

- [1] NR—BS Radio Transmission and Reception, document TS 38. 104 (V15.2.0), 3GPP, Jun. 2018. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/38_series/38.104/
- [2] A. Vosoogh, M. S. Sorkherizi, A. U. Zaman, J. Yang, and A. A. Kishk, "An integrated Ka-band diplexer-antenna array module based on gap waveguide technology with simple mechanical assembly and no electrical contact requirements," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 2, pp. 962–972, Feb. 2018.
- [3] W. El-Halwagy, R. Mirzavand, J. Melzer, M. Hossain, and P. Mousavi, "Investigation of wideband substrate-integrated vertically-polarized electric dipole antenna and arrays for mm-wave 5G mobile devices," *IEEE Access*, vol. 6, pp. 2415–2457, 2018.
- [4] C. Hannachi and S. O. Tatu, "A compact V-band planar gap-coupled 4×1 antenna array: Improved design and analysis," *IEEE Access*, vol. 5, pp. 8763–8770, 2017.
- [5] J. Guo, S. Liao, Q. Xue, and S. Xiao, "Planar aperture antenna with high gain and high aperture efficiency for 60-GHz applications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6262–6273, Dec. 2017.
- [6] Z.-W. Miao et al., "140 GHz high-gain LTCC-integrated transmit-array antenna using a wideband SIW aperture-coupling phase delay structure," *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 182–190, Jan. 2018.
- [7] Z. Chen, H. Liu, J. Yu, and X. Chen, "High gain, broadband and dual-polarized substrate integrated waveguide cavity-backed slot antenna array for 60 GHz band," *IEEE Access*, vol. 6, pp. 31012–31022, 2018.
- [8] Y. She, R. Fujino, J. Hirokawa, M. Ando, D. Hanatani, and M. Fujimoto, "LTCC oversized rectangular waveguide slot array antenna with air-layer in the radiating part in the millimeter-wave band," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1777–1783, Apr. 2013.
- [9] Y. Tyagi, P. Mevada, S. Chakrabarty, and R. Jyoti, "High-efficiency broadband slotted waveguide array antenna," *IET Microw., Antennas Propag.*, vol. 11, no. 10, pp. 1401–1408, Aug. 2017.
- [10] G.-L. Huang, S.-G. Zhou, T.-H. Chio, H.-T. Hui, and T.-S. Yeo, "A low profile and low sidelobe wideband slot antenna array fed by an amplitude-tapering waveguide feed-network," *IEEE Trans. Antennas Propag.*, vol. 63, no. 1, pp. 419–423, Jan. 2015.
- [11] G. P. Le Sage, "3D printed waveguide slot array antennas," *IEEE Access*, vol. 4, pp. 1258–1265, 2016.
- [12] Q.-L. Yang, Y.-L. Ban, J.-W. Lian, Z.-F. Yu, and B. Wu, "SIW butler matrix with modified hybrid coupler for slot antenna array," *IEEE Access*, vol. 4, pp. 9561–9569, 2016.
- [13] Y. Miura, J. Hirokawa, M. Ando, Y. Shibuya, and G. Yoshida, "Double-layer full-corporate-feed hollow-waveguide slot array antenna in the 60-GHz band," *IEEE Trans. Antennas Propag.*, vol. 59, no. 8, pp. 2844–2851, Aug. 2011.
- [14] D. Kim, M. Zhang, J. Hirokawa, and M. Ando, "Design and fabrication of a dual-polarization waveguide slot array antenna with high isolation and high antenna efficiency for the 60 GHz band," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3019–3027, Jun. 2014.
- [15] T. Tomura, J. Hirokawa, T. Hirano, and M. Ando, "A 45° linearly polarized hollow-waveguide 16×16 -slot array antenna covering 71–86 GHz band," *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 5061–5067, Oct. 2014.
- [16] A. Farahbakhsh, D. Zarifi, and A. U. Zaman, "A mmWave wideband slot array antenna based on ridge gap waveguide with 30% bandwidth," *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 1008–1013, Feb. 2018.
- [17] W. W. Milroy, "The continuous transverse stub (CTS) array: Basic theory experiment and application," in *Proc. Antenna Appl. Symp.*, vol. 2, Sep. 1991, pp. 253–283.
- [18] Y. Xu, H. Dong, Y. Liu, and P. Zhang, "Continuous transverse stub (CTS) array antenna," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Oct. 2012, pp. 1083–1086.
- [19] T. Potelon et al., "A low-profile broadband 32-slot continuous transverse stub array for backhaul applications E-band," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6307–6316, Dec. 2017.
- [20] F. F. Manzano et al., "A multilayer LTCC solution for integrating 5G access point antenna modules," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 7, pp. 2272–2283, Jul. 2016.
- [21] F. F. Manzano, M. Ettorre, M. Casaletti, N. Capet, and R. Sauleau, "Active impedance of infinite parallel-fed continuous transverse stub arrays," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 3291–3297, Jul. 2015.
- [22] D. M. Pozar, *Microwave Engineering*, 3rd ed. Hoboken, NJ, USA: Wiley, 2012.
- [23] F. F. Manzano, R. Sauleau, N. Capet, and M. Ettorre, "Mode matching analysis of an E-plane 90° bend with a square step in parallel-plate waveguide," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2187–2190, 2017.
- [24] Y. You, Y. Lu, Q. You, Y. Wang, J. Huang, and M. J. Lancaster, "Millimeter-wave high-gain frequency-scanned antenna based on waveguide continuous transverse stubs," *IEEE Trans. Antennas Propag.*, vol. 66, no. 11, pp. 6370–6375, Nov. 2018.
- [25] M. Samardzija, T. Kai, J. Hirokawa, and M. Ando, "Single-layer waveguide feed for uniform plane wave in oversized-rectangular waveguide with hard-surface sidewalls," *IEEE Trans. Antennas Propag.*, vol. 54, no. 10, pp. 2813–2819, Oct. 2006.
- [26] Q.-X. Chu, Z.-Y. Kang, Q.-S. Wu, and D.-Y. Mo, "An in-phase output Ka-band traveling-wave power divider/combiner using double ridge waveguide couplers," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 9, pp. 3247–3253, Sep. 2013.



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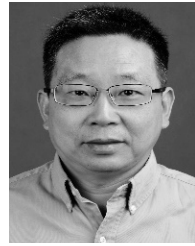
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